NOISE MEASUREMENT SYSTEM AND METHOD

Background of the Invention

One measure of the integrity of a communication system is the amount of noise present within the system. Characterizing the noise of a communication system involves measuring noise power within one or more specified frequency bands, shown for example in the exemplary noise spectrum of Figure 1. Measuring noise power, in turn, involves measuring or estimating the statistics of the noise, which is inherently random.

A conventional noise figure meter (shown in Figure 2) provides accurate measurements of noise power within a designated frequency band. In the noise figure meter, noise within the frequency band is down-converted and measured by a noise power detector. Because the noise figure meter includes multiple frequency conversion stages, the noise figure meters are typically expensive to manufacture.

Conventional direct conversion receivers (shown in Figures 3A-3B) are also used to measure noise power. A direct conversion receiver is typically less expensive to manufacture than a noise figure meter because the receiver includes only a single frequency conversion stage. The direct conversion receiver converts the noise within a frequency band (for example, frequency band ***c*** shown in Figure 3C) to a baseband noise signal (shown in Figure 3D) that is measured by a noise power detector (as shown in Figure 3A) or by a narrow-band analog-to-digital converter (as shown in Figure 3B). However, these direct conversion receivers are not as accurate as noise figure meters. One measure of error, the variance of the measured noise power, is substantially higher for the direct conversion receiver than for the noise figure meter. For example, the variance of the noise power measured by a typical direct conversion receiver is approximately twice as great as the variance of the noise power measured by a noise figure meter.

An alternative approach to noise power measurement is shown in Figure 4A. In this approach, a frequency conversion stage causes upper and lower noise sidebands to overlap within a single measurement band B. Figures 4B-4D show these overlapping noise sidebands within the single measurement band B as a local oscillator within the frequency conversion stage is stepped in frequency between frequencies f_1, f_2 and f_3. A noise power detector then measures the noise power in the single measurement band B, with the local oscillator at each of the stepped frequencies. While this approach can take advantage of low-cost signal processing to extract the noise power in a designated frequency band (for example, frequency band ***c***) based on the overlapping noise sidebands, measurement accuracy is not as good as that of the conventional noise figure meter. For example, the variance of the noise power measured using this approach is approximately three times as great as the variance that results when noise power is measured using a conventional noise figure meter.

In view of the above, there is a need for an accurate noise measurement system that does not rely on the multiple frequency conversion stages of a noise figure meter.

Summary of the Invention

A noise measurement system according to embodiments of the present invention measures noise power within one or more designated frequency bands of an applied signal. The noise measurement system includes a frequency converter that frequency translates the applied signal by a set of equally spaced frequencies to form a corresponding set of intermediate frequency signals. A sampler in the noise measurement system measures the noise in at least two measurement bands of each of the intermediate frequency signals that are separated by the frequency spacing of the equally spaced frequencies. The noise

measurement system also includes a signal processor that determines the noise power in the designated frequency band of the applied signal based on the noise measurements by the sampler. Alternative embodiments of the present invention are directed to a noise measurement method.

Brief Description of the Drawings

Figure 1 shows a series of frequency bands within an exemplary noise spectrum.

Figure 2 shows a conventional noise figure meter.

Figures 3A-3D show conventional direct conversion receivers and associated measurement noise spectra.

Figures 4A-4D show alternative conventional noise measurement receivers and associated measurement noise spectra.

Figures 5 shows a noise measurement system according to embodiments of the present invention.

Figures 6A-6D show noise spectra associated with the noise measurement system of Figure 5.

Figure 7 shows a noise measurement method according to alternative embodiments of the present invention.

Figure 8 shows a plot of measurement accuracy of the noise measurement system and noise measurement method according to the embodiments of the present invention.

Detailed Description of the Embodiments

Figure 6A shows an exemplary signal S_{IN} with a series of frequency bands ***a-e*** designated within the spectrum of the signal S_{IN}. A noise measurement system 10 and noise measurement method 20 according to embodiments of the present invention measure noise power within one or more of the frequency bands ***a-e***. The noise measurement system 10 (shown in Figure 5) includes a frequency converter 12 cascaded with a sampler 14 and a signal processor 16. A display 18 or other output device optionally coupled to the signal processor 16 enables the noise power measured by the noise measurement system 10 to be displayed.

The frequency converter 12 typically includes a preselector FIL, a mixer M, a local oscillator LO, and output filters HP, LP. The preselector FIL limits the bandwidth of the signal S_{IN} prior to application to the mixer M to reduce the effect of higher order mixing products that cause unwanted noise sidebands to fall within the bandwidth of intermediate frequency signals IF_1- IF_n at the output of the frequency converter 12. In this example, the mixer M is a double-balanced mixer. However, any other suitable frequency translation device is alternatively used in the frequency converter 12.

The local oscillator LO is any suitable signal source capable of providing a succession of local oscillator signals SLO_1-SLO_n to the mixer M, wherein each of the local oscillator signals has a frequency belonging to a designated set of equally-spaced frequencies f_1-f_n. In a typical implementation, the local oscillator LO is signal source that can be stepped in frequency, or a comb generator with an adjustable filter that provides the local oscillator signal SLO_1-SLO_n successively at each of the frequencies f_1-f_n.

The output filter HP is a high pass filter that filters close-in noise from the local oscillator LO that gets translated by the mixer M into the frequency range of the

intermediate frequency signals IF_1-IF_n. The output filter LP is typically a low pass filter that limits the bandwidth of each of the intermediate frequency signals IF_1-IF_n present at the output of the frequency converter 12 to prevent aliasing when the intermediate frequency signals are each sampled by the sampler 14.

The sampler 14 is an analog-to-digital (A-to-D) converter, signal digitizer or other type of sampling system suitable for sampling each of the intermediate frequency signals IF_1-IF_n at the output of the frequency converter 12. The signal processor 16, in this example implemented with a digital signal processor (DSP), processes the samples of the intermediate frequency signals IF_1-IF_n acquired by the sampler 14 to determine the noise power in one or more of the frequency bands ***a-e*** within the signal S_{IN}.

To determine the noise power within a designated frequency band within the signal S_{IN}, the frequency converter 12 frequency translates the signal S_{IN} to provide the intermediate frequency signals IF_1-IF_n at the input to the sampler 14. This frequency translation includes mixing the signal S_{IN} with each of the local oscillator signals SLO_1-SLO_n. The local oscillator signals SLO_1-SLO_n, having the corresponding frequencies f_1-f_n, are separated by a frequency spacing f_S. Figures 6B, 6C, 6D show examples of three intermediate frequency signals IF_1-IF_n that result at the output of the frequency converter 12 when the signal S_{IN} is translated by three equally-spaced frequencies f1-f3. The resulting intermediate frequency signals IF_1-IF_3 each include a superposition of overlapping upper and lower spectral sidebands. The upper sidebands USB_X and lower sidebands LSB_X, though overlapping, are shown vertically offset from each other in Figures 6B-6D.

Noise of each of the intermediate frequency signals, for example intermediate frequency signals IF_1-IF_3, is measured in two or more measurement bands B_1-B_K defined

within the spectrum of each of the intermediate frequency signals IF_1-IF_3. The measurement bands B_1-B_K are each separated by the frequency spacing f_S that separates the frequencies f_1-f_n. To measure the noise of the intermediate frequency signals, the sampler 14 acquires samples of each of the intermediate frequency signals at a sufficiently high sampling rate to accommodate signal bandwidths that are wider than the frequency spacing f_S of the local oscillator signals SLO_1-SLO_n. Particularly, the sampling rate of the sampler 14 is suitably high to satisfy the Nyquist criteria for the two or more defined measurement bands B_1-B_K when separated by the frequency spacing f_S. These measurement bands B_1-B_K are defined in the intermediate frequency signals IF_1-IF_n either by filtering the intermediate frequency signals prior to the sampling by the sampler 14, or by digital filtering or other signal processing of the samples that are acquired of the intermediate frequency signals IF_1-IF_n by the sampler 14. Depending on the frequencies f_1-f_n of the local oscillator signals SLO_1-SLO_n, various frequency bands ***a-e*** of the signal S_{IN} overlap within two or more of the measurement bands B_1-B_K.

Figure 6B shows the spectrum of the intermediate frequency signal IF_1 that results at a time t1 when the local oscillator LO providing the local oscillator signal SLO_1 has a frequency f_1. Noise components ***b1*** and ***b2*** of the frequency band ***b*** in the signal S_{IN} are shown overlapping within a measurement band B_1 in the intermediate frequency signal IF_1. Frequency bands ***a*** and ***c*** in the signal S_{IN} overlap within the measurement band B_2 in the intermediate frequency signal IF_1. Measuring the overlapping noise components ***b1***, ***b2*** in the measurement band B_1, results in the noise measurement M_b. Measuring noise of the overlapping frequency bands ***a*** and ***c*** in the measurement band B_2 results in a noise measurement $M_{ac} = N_a+N_c$. The noise measurement M_{ac} represents the sum of the noise power N_a in the frequency band ***a*** translated to a lower sideband LSB_1 in the intermediate

frequency signal IF_1, and the noise power N_c in the frequency band ***c*** translated to an overlapping upper sideband USB_1 of the intermediate frequency signal IF_1.

Figure 6C shows the spectrum of the intermediate frequency signal IF_2 that results when the local oscillator LO providing the local oscillator signal SLO_2 has a frequency f_2. Noise components ***c1*** and ***c2*** of the frequency band ***c*** in the signal S_{IN} are shown overlapping within a measurement band B_1 in the intermediate frequency signal IF_2. Frequency bands ***b*** and ***d*** in the signal S_{IN} overlap within the measurement band B_2 in the intermediate frequency signal IF_2. Frequency bands ***a*** and ***e*** in the signal S_{IN} overlap within the measurement band B_3 in the intermediate frequency signal IF_2. Measuring overlapping noise components ***c1***, ***c2*** in the measurement band B_1 results in the noise measurement M_c. Measuring noise of the overlapping frequency bands ***b*** and ***d*** in the measurement band B_2 results in a noise measurement $M_{bd}=N_b+N_d$. The noise measurement M_{bd} represents the sum of the noise power N_b in the frequency band ***b*** translated to a lower sideband LSB_2 in the intermediate frequency signal IF_2, and the noise power N_d in the frequency band ***d*** translated to an overlapping upper sideband USB_2 of the intermediate frequency signal IF_2. Measuring noise of the overlapping frequency bands ***a*** and ***e*** in the measurement band B_3 results in a noise measurement $M_{ae}=N_a+N_e$. The noise measurement M_{ae} represents the sum of the noise power N_a in the frequency band ***a*** translated to a lower sideband LSB_2 in the intermediate frequency signal IF_2, and the noise power N_e in the frequency band ***e*** translated to an overlapping upper sideband USB_2 of the intermediate frequency signal IF_2.

Figure 6D shows the spectrum of the intermediate frequency signal IF_3 that results when the local oscillator LO providing the local oscillator signal SLO_3 has a frequency f_3. Noise components ***d1*** and ***d2*** of the frequency band ***d*** in the signal S_{IN} are shown

overlapping within a measurement band B_1 in the intermediate frequency signal IF_3. Frequency bands ***c*** and ***e*** in the signal S_{IN} overlap within the measurement band B_2 in the intermediate frequency signal IF_3. Measuring the overlapping noise components ***d1***, ***d2*** in the measurement band B_1 results in the noise measurement M_d. Measuring noise of the overlapping frequency bands ***c*** and ***e*** in the measurement band B_2 results in a noise measurement $M_{ce} = N_c+N_e$. The noise measurement M_{ce} represents the sum of the noise power N_c in the frequency band ***e*** translated to a lower sideband LSB_3 in the intermediate frequency signal IF_3, and the noise power N_e in the frequency band ***e*** translated to an overlapping upper sideband USB_3 of the intermediate frequency signal IF_3.

The noise power in one or more of the frequency bands ***a-e*** of the signal S_{IN} is determined by the signal processor 16 based on the noise measurements. In this example, the noise power determination is facilitated by expressing the relationship between the noise measurements M_b, M_c, M_d, M_{ac}, M_{bd}, M_{ae}, M_{ce}, and the noise powers N_a, N_b, N_c, N_d, N_e in the frequency bands ***a-e***, in a matrix equation 1.

$$\begin{bmatrix} 01000 \\ 00100 \\ 00010 \\ 10100 \\ 01010 \\ 10001 \\ 00101 \end{bmatrix} * \begin{bmatrix} N_a \\ N_b \\ N_c \\ N_d \\ N_e \end{bmatrix} = \begin{bmatrix} M_b \\ M_c \\ M_d \\ M_{ac} \\ M_{bd} \\ M_{ae} \\ M_{ce} \end{bmatrix} \qquad (1)$$

In an alternative notation, Equation 1 is expressed by the matrix equation $[H]*[N]=[M]$. Applying the least squares method, described for example in by Charles W. Therrien, *Discrete Random Signals and Statistical Signal Processing*, pages 518-523,

ISBN 0-13-852112-3, herein incorporated by reference, to the matrix equation 1 leads to the solution for the noise power matrix [N] in equation 2, where $[H]^T$ is the transpose of the matrix [H].

$$[N] = \{[H]^T * [H]\}^{-1} * [H]^T * [M] \qquad (2)$$

This solution for the noise power matrix [N] is expressed explicitly in equation 3 for the example where the set of frequencies f_1-f_n is made up of the three frequencies f_1, f_2, f_3.

$$\begin{bmatrix} Na \\ Nb \\ Nc \\ Nd \\ Ne \end{bmatrix} = \left(\frac{1}{21}\right) \begin{bmatrix} -3Mc + 12Mac + 9Mae - 9Mce \\ 14Mb - 7Md + 7Mbd \\ 9Mc + 6Mac - 6Mae + 6Mce \\ -7Mb + 14Md + 7Mbd \\ -3Mc - 9Mac + 9Mae + 12Mce \end{bmatrix} \qquad (3)$$

From equation 3, the noise power in one or more of the frequency bands ***a-e*** of the signal S_{IN} is readily available. For example, the noise power in the frequency band ***c*** of the signal S_{IN} is expressed in terms of the measured powers as follows:

$$Nc = \frac{6M_{ac} - 6M_{ae} + 9M_c + 6M_{ce}}{21} = \frac{2M_{ac} - 2M_{ae} + 3M_c + 2M_{ce}}{7}.$$

While the noise power is determined within the frequency band ***c*** of the signal S_{IN} for the purpose of illustration, the noise power can also be determined in other frequency bands within the signal S_{IN}.

Due to the random nature of noise in the signal S_{IN}, the noise power (for example N_c) provides a measure of the statistics of the noise in the frequency band ***c***. The measured noise expressed in the matrix [M] is also a random variable and the variance of the noise measurements in the matrix [M] provides a measure of uncertainty in the noise

measurements. In an exemplary noise measurement, where the noise measurements are performed with the local oscillator signals SLO_1-SLO_3 at the frequencies f_1-f_3, the variance of the noise measurement M_b is 1.56, the variance of the noise measurement M_c is 1.35 and the variance of the noise measurement M_d is 1.56, where each of these variances is normalized to the variance that results when a conventional noise figure meter is used to determine the noise power within a designated frequency band of the signal S_{IN}.

The noise power in this example has been determined based on the frequency translation of the signal S_{IN} by three frequencies f_1-f_3 for the purpose of illustration. When more than the three local oscillator frequencies f_1-f_3 are used in the frequency translations and when frequency bands in addition to the frequency bands ***a-e*** are designated in the signal S_{IN}, the accuracy of the noise power measurements increases. Figure 8 shows the resulting increase in measurement accuracy, depicted as a decrease in normalized measurement variance, as the number n of local oscillator frequencies f_1- f_n increases.

According to alternative embodiments of the present invention, noise power is determined by a noise measurement method 20 shown in the flow diagram of Figure 7. The noise measurement method 20, which includes steps 22-26, determines the noise power within one or more of the designated frequency bands ***a-e*** of the signal S_{IN}. Step 22 includes frequency translating the signal S_{IN} by the set of equally spaced frequencies f_1-f_n to form the intermediate frequency signals IF_1-IF_n. frequency translating typically includes mixing the signal S_{IN} with each of the local oscillator signals SLO_1-SLO_n.

Step 24 includes measuring the noise in the two or more measurement bands B_1-B_K within each of the intermediate frequency signals IF_1-IF_n that are separated by the frequency spacing f_S of the equally spaced frequencies f_1-f_n. The noise measurement includes acquiring samples of each of the intermediate frequency signals IF_1-IF_n at a

sufficiently high sampling rate to accommodate signal bandwidths of the two or more defined measurement bands B_1-B_K that are separated by the frequency spacing f_S. The measurement bands B_1-B_K are defined in the intermediate frequency signals IF_1-IF_n either by filtering the intermediate frequency signals prior to the sampling by the sampler 14, or by digital filtering or other signal processing of the samples that are acquired of the intermediate frequency signals IF_1-IF_n by the sampler 14. In step 26, noise power in the designated frequency band of the signal S_{IN} is determined based on the noise measurements performed in step 24. In one example, the noise power in one or more designated frequency bands of the signal S_{IN} is determined by solution of the matrix equation 1 and by application of the least square method.

While the embodiments of the present invention have been illustrated in detail, it should be apparent that modifications and adaptations to these embodiments may occur to one skilled in the art without departing from the scope of the present invention as set forth in the following claims.